Identification of climatic and management factors influencing wheat’s yield variability using AgMERRA dataset and DSSAT model across a temperate region

Masume Farhadi
Ferdowsi University of Mashhad
Muhammad Bannayan
Ferdowsi University of Mashhad
Muhammad Hassan Fallah
Ferdowsi University of Mashhad
Mohsen Jahan (jahan@ferdowsi.um.ac.ir)
Ferdowsi University of Mashhad

Research Article

Keywords: Spatio-temporal variables, Simulated data set, Wheat phenology, Climate variability, growth stage

Posted Date: August 5th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1924947/v1

Abstract

One of the main challenges of current agriculture to ensure food security is the development of strategies to deal with potential negative impacts and adaptation to climate variability. This study has conducted to determine climatic and management factors influencing wheat yield variability throughout a temperate region in Northeastern Iran in the period of 1980–2010. The growth stages and yield of wheat crop were simulated with DSAAT model, using AgMERRA gridded dataset and the effect of climatic variables on yield was identified using Panel Data Regression (PDA). According to the results, 63% of the changes in irrigated wheat yield are explained by environmental factors (temperature and precipitation) and 37% by management factors. PDA revealed that among the climatic variables, the number of temperatures above 30 ^{o}C during the growing season, mean temperature, amount and frequency of precipitation have a significant effect on irrigated wheat yield ($p \leq 0.05$). The length of wheat growing season throughout the study region were decreased by 26 days during the study period. The management practices, including the provision of inputs such as chemical fertilizers, modified seeds, tillage machinery and equipment, information transfer and the penetration of knowledge in the field, increase yields by averaged if 5 kg per year in study region. In general, employing the effective management methods, in particular selecting the appropriate planting date that could be resulted in better adaptation of the phenological stages of wheat to environmental conditions, can improve wheat yield. The results of this research indicate that using valid AgMERRA meteorological dataset as input for DSSAT crop model could produce reliable simulations which in turn could be employed by food policy and decision makers, farmers and managers in a temperate region.

1. Introduction

Climate change and reducing of natural resources have strongly affected the world food security. On the other hand, have been expected that world population will be increased to 9.7 billion inhabitants by 2050 (Arun & Ghimire, 2019). Wheat is a major cereal crop around the world and shares about 21% of the global food production (Curtis & Halford, 2014). Demand for wheat in developing countries is projected to increase by 60% by 2050 (Nelson et al., 2009). One of the agricultural strategies to ensure food security is cope with negative impacts of climate change and variability (Raymundo et al., 2018). Global warming is expected roughly 1℃ by 2030, relative to the late twentieth century(Solomon et al., 2007). Therefore, identification of vulnerable areas and adaptive operations are very important to maintain the present level of food production, moreover achieve sustainable production (Sanjani et al., 2011). Climatic variables such as air temperature and precipitation affect crop yields (Alexandrov & Hogenboom, 2000; Bannayan et al., 2010). Temporal and spatial fluctuations in yield are due to differences in input levels, agricultural developments, as well as soil and climate conditions (Bannayan et al., 2018; Yaghoubi et al., 2020). Despite of major developments in cropping systems and technologies, management of climate induced variables in yields is often inefficient and simple indicators of growing season temperatures and precipitation explain 30% of variations in global average yields (Lobell & Field, 2007). The result of a study shows that in globally, climate variability accounts for roughly a third (32–39%) of the observed yield variability (Ray et al., 2015). Crop production will decrease significantly and growing period is shortened with warming (Gohari et al., 2013). A study revealed that 28% – 34% changes in yield could be explain with change in agro climatic conditions (Iizumi & Ramankutty, 2010). Asian farmers almost attempt to cope with annual climatic variability so adaptation acts and management practices such as taking optimum regimes of irrigation to hedge against drought and heat stress harmful consequences is necessary (Jain et al., 2015; Nassiri-Mahallati & Jahan, 2020). Agricultural production is mainly characterized by high levels of uncertainty and risks. Natural disasters, pests, disease, early cold in autumn, late cold in spring and drought hits to farmers economy (Sookhtanlo & Sarani, 2019). By studying plant phenology, the effect of climate variability on plant growth and yield can be analyzed, and in the following, provide the best suggestions for coping and adaptation (Jahan and Nassiri-Mahallati, 2022). Studying wheat phenology could help farmers to confront with climate conditions (Ren et al., 2019). Temperatures above 30°C cause damage to the photosynthetic system in wheat leaves, resulting in reduced grain filling and yield (Asseng et al., 2011). Therefore, farmers' access to agricultural facilities and adaptation management of environmental stresses are effective in reducing yield and achieving food security (Arshad & Krupnik, 2016; Jahan & Nassiri-Mahallati, 2022) .

Estimating yield and its variability are essential for analysis of food security, assessing impact of climate variability on crop production, development and employing of crop management decision-support tools, supporting and target agronomic research and policy (Jahan & Nassiri-Mahallati, 2022). Regarding the importance of climate change, various tools have been developed to measure its effects. One of the relatively low cost, accurate and fast solution is the use of modeling approach and crop growth simulation models (Ruane et al., 2015). On the other hand, crop simulation models require high-quality and long-term historical daily weather data (Wallach et al., 2014; Van Wart et al., 2015). Almost all agricultural climatic indices are calculated based on temperature and precipitation. According to the World Meteorological Organization's standard, meteorological data for at least thirty years are required for climate studies (Burroughs, 2003). However, in many regions of the world that often face climate variability and vulnerability of their agricultural production, most weather stations only have available daily weather data for a few years and also may not cover all required variables for crop models (Lobell & Burk, 2010; Van wart et al. 2015). One of the challenges in obtaining meteorological data is the small number and dispersion of meteorological stations and missing data (Bender & Sentelhas, 2018). Gridded weather data have been used as alternatives in regions where observed weather data are not available (Van Wart et al., 2015). AgMERRA)Agricultural Modern-Era Retrospective analysis for Research and Applications) is the result of the reanalysis of data from satellites MERRA (Modern-Era Retrospective Analysis for Research and Applications(, PERSIANN (Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks) and CMORPH (Climate prediction center morphing method) that used (Joyce et al., 2004) and the observed data of synoptic stations in 2324 important agricultural areas across the world. Agricultural researches need to daily, high resolution of meteorological data that are available at AgMERRA global gridded climate data set with (0.25° × 0.25° horizontal resolution for precipitation, wind speed, and relative humidity at the time of maximum temperature ‘minimum relative humidity’), 0.5° × 0.5° for the minimum and maximum temperature (T_{max} and T_{min}), and 1° × 1° for solar radiation) (White et al., 2008; Ruane et al., 2015). The gridded weather database are usually derived from global circulation computer models, remotely sensed satellites data, or interpolated land station data (Van Wart et al., 2013)

North Khorasan province with 28179 km^2 area is located in the Northeast, Iran. It has seven meteorological stations that historical meteorological data are not available for or have missing values. On the other hand, assuming the completion and availability of long-term meteorological data, this number of synoptic stations are not sufficient to conduct climatic studies and implement simulation models of crop yields in the wide area and therefore do not have the necessary accuracy. According to official statistics, the area under irrigated and rain-fed wheat cultivation in 2018 in north Khorasan Province was 146,274 hectares, which is the dominant crop in the province. Wheat has long been a major crop in the region and the farmers' economy depends on it.

The objectives of this study is, at first, to investigate the trend of historical wheat yield and identify the share of environmental and managerial factors influencing it. The second is, simulating the growth and development of irrigated wheat using valid AgMERRA forcing dataset, by the DSSAT crop model, which has already been calibrated and validated for different areas of wheat cultivation in Iran. The third is, finding the best recommendable management option for wheat cultivation in study region to mitigate climate variability and uncertainty. The results of this research help to make adaptive management, farm level decisions and appropriate operations to deal with environmental changes and climate variability.

2. Materials And Methods

In this research, year-to-year variability in observed wheat yields and growth stages associated with variations in climate were analyzed using gridded temperature and precipitation data and assess how wheat yield changes with stress degree-days on a spatiotemporal scale.

2.1. Study area

This study was conducted in north Khorasan province of Iran with 28179 km^2 area and seven regions (Bojnord, Shirvan, Farooj, Esfarayen, Raz-Jargalan, Mane-Semelghan, Jajarm). It is located in the geographical coordinates of 36^{o} 27' to 38 ^{o} 17' N and 55 ^{o} 54' to 58 ^{o} 25' E. This area with a diverse and often temperate mountainous climate is located in Northeastern Iran at an average altitude of 1326 m above sea level.

2.2. Collection of data and information

2.2.1. Measured and gridded weather data

Measured Weather Data (MWD) were retrieved from seven locations across the north Khorasan province. Historical daily measured weather data of maximum and minimum air temperature (Tmax, Tmin), sunshine hours (R), relative humidity (RH) and precipitation (P), from 1980 to 2010, and for two stations (Bojnord and Esfarayen) up to 2016, were obtained from the Organization of Meteorology of North Khorasan (OMNK). The geographical location of north Khorasan province and distribution of weather data stations have been presented in Table1. The AgMERRA dataset for the period of 1980–2010 was downloaded in NetCDF format from NASA official website (http://data.giss.nasa.gov/impacts/agmipcf/agmerra) then was analyzed and converted to appropriate format in R software using ‘ncdf4’ package (Bosilovich et al., 2015).

2.2.1.2. Filling gaps in the meteorological database

Gaps in measured weather data (Tmax, Tmin, Solar radiation: Rs, rainfall, wind speed, and RH) can be filled in with data from the gridded databases such as AgMERRA. AgMERRA with observed datasets from weather station networks and satellites, available on a daily temporal scale, for the period between 1980 and 2010, at 0.25° × 0.25° horizontal resolution (Rienecker et al., 2011).

2.2.1.3. Solar radiation estimation

As solar radiation (Rs) is not commonly recorded by conventional weather stations, so its values were calculated from sunshine hours (*n*) data using the Angstrom-Prescott equation (Angstrom, 1924; Prescott, 1940) as follow:

$Rs = (as + bs^{n} /N) Ra$ Eq. 1

where Rs is the solar radiation at the ground surface (MJ m^{-2} day^{-1}), Ra is the radiation above the atmosphere (MJ m^{-2} day^{-1}), n represents the actual sunshine duration (h), N is day length (h), and a and b are Angstrom-Prescott coefficients.

2.2.1.4. The AgMERRA dataset simulations

For each weather variable, goodness-of-fit indices between observations and AgMERRA were calculated and evaluated for the grid cell in which meteorological stations were located. The full description of validity and possibility of using AgMERRA Networked Dataset in Northeastern Iran is given by Farhadi et al. (2021), they reported that the validity results of the AgMERRA simulations indicated its robustness and power to produce meteorological data series in Northeastern Iran.

2.2.1.5. Soil data

The soil properties including texture, structure, root penetration depth and electrical conductivity were obtained from the World Soil Database (ISRIC) and extracted by ArcGIS software. These data can be downloaded for the globe with a resolution of $0.5^{o} \times 0.5^{o}$. This database contains 1125 soil profiles distributed worldwide, which are referenced and classified according to the FAO system (Batjes Niels, 2012).

2.2.3. Crop management data

The required data including cultivar, planting date, sowing depth, type and amount of inputs were obtained from local organizations, farmers and extension agents. The average historical yield of irrigated wheat from 1980 to 2017 in each area were extracted from official reports (www.maj.ir).

2.2.4. Data analysis & Modeling

2.2.4.1. Climatic variability and managerial factors

To determine the effect of climatic and management factors on wheat yield, the historical observational yield trend was studied. The trend of long-term yield changes due to management factors and its year-to-year fluctuations due to climate variability were investigated using regression models. The slope of the fitted line on the yield change curve indicates the impact of management factors over time.

2.2.4.2. Crop yield simulations

To investigate the growth characteristics of the plant due to environmental factors, the growth stages were simulated using CSM-CERES (Cropping System Model-Crop Environment Resource Synthesis) model in the DSSAT (Decision Support System for Agro technology Transfer) Ver. 4.7 software package. This model simulates plant growth on a daily time scale. In this study, the genetic coefficients of irrigated wheat cultivar, which has been previously calibrated and evaluated, was used to implement the model (Fallah et al., 2021). The CSM-CERES model inputs include rainfall, minimum temperature, maximum temperature, solar radiation, conventional planting date in the study area (October 15), number of irrigations (6 times and each time at the rate of 1000 m^3 ha^{-1}), the planting density of 250–300 plants per m^2 was considered.

To determine the effect of temperature and precipitation on yield (Bannayan et al., 2010), recorded yield data were employed, and the years with good and poor yield were examined for some traits. These traits include the length of the growing season, the amount and distribution of precipitation during the growing season, the length of grain filling phase (from anthesis to the end of the soft dough stage, Step 40 to 80 Zadox scale) (Poole, 2005), number of days with temperatures above 30°C during the growing season, minimum, maximum and average temperatures during the growing season were recorded and arranged in for each region and year (according to available meteorological data, in a period of 30 to 36 years) using MS-Excel software.

To study the trend of yield changes and determine the effect of climatic and managerial factors on it, the growth stages and yield of irrigated wheat were simulated by DSAAT 4.7 crop model and then evaluated and validated with the observed yield. The trend of long-term yield changes reflects the impact of management factors and its fluctuations from year to year due to climate change. Finally, the years with good and poor yield were analyzed in terms of sensitive growth stages and the occurrence of temperature and rainfall stress.

2.2.4.3. Panel Data Analysis (PDA)

To determine the effect of environmental variables on wheat yield over the studied period in different regions, the panel data analysis was employed (Lobell & Burke, 2010). PDA is actually a combination of time series and spatial analysis (Eq. 2).

$$ {Y}_{it}=\beta {\text{X}}_{it}+\alpha {\text{Z}}_{i}+{\epsilon}_{it} $$ Eq. 2

where Y is the dependent variable, X is the independent variable, ϵ is the error at location i and at time t, and Z_i is a variable that shows the special characteristics of each location (heterogeneity of sections) or each region. If Z_i contains only one constant term that is the same for all groups, then the equation will be as follows (Eq. 3):

$$ {Y}_{it}=\beta {\text{X}}_{it}+\alpha +{\epsilon}_{it} $$ Eq. 3

In this case, the model considered as the aggregated or pooled model (cross-sectional heterogeneities are not significant and are not present in the model). In this regression mode, the common intercept (common alpha) is considered for all sections (all regions or places). Flimer's test is used to determine cumulative regression (pooled) or the model with effects (panel). If there is a significant difference in the model between different sections, and Z_i is correlated with X_i (independent variables on the right side of the model), then for each group, there is an intercept (α_i), whose equation is as follow (Eq. 4):

$$ {Y}_{it}=\beta {\text{X}}_{it}+{\alpha }_{i}+{\epsilon}_{it} $$ Eq. 4

Here, $\alpha_i = \alpha Z_i$, which includes all observable effects and represents a conditional mean that can be estimated. In this approach, which called the model with "fixed effects", each group is assigned a fixed value such as α_i.

3. Results And Discussion

To study the trend of yield changes and determine the effect of climatic and managerial factors on it, the growth stages and yield of irrigated wheat were simulated and then evaluated and validated with the observed yield. The trend of long-term yield changes reflects the impact of management factors and its fluctuations from year to year due to climate change. Finally, the years with good and poor yield were analyzed in terms of sensitive growth stages and the occurrence of temperature and rainfall stress.

3.1. Trend of yield changes

The average yield of irrigated wheat over 38 years, with a very gentle upward slope, has had an almost constant trend due to managerial factors. In other words, all management practices, including the provision of inputs such as chemical fertilizers, modified seeds, tillage machinery and equipment, information transfer and the penetration of knowledge in the field, increase yields by averaged of 5 kg per year (for seven studied regions, by 12.63, 9.90, 1.63, 4.67, 4.52, 0.89, 1.41 kg per year, respectively) (Fig.1). This increase in yield was related to the influence of management operations (in particular cultivar and technology/mechanization improvement). To investigate the effect of environmental variables as an important variable on wheat yield, growth stages were simulated using DSSAT model. The coefficient of determination (R^2) of the observed yield values with the estimated yield of wheat were 0.91, 0.70, 0.71, 0.68 and 0.69 which indicates the appropriate accuracy of the model in predicting yield (Fig. 2).

It has been reported that one third of yield variation can be explained by climatic variables (Ray et al., 2015). The researches conducted on the role of environmental factors on yield shows a negative correlation between temperature and yield. The reports indicate that global wheat production decreases by 6% for every one degree Celsius increase in temperature (Arshad and Krupnik, 2016; Asseng et al., 2011). The results of a study conducted on a global scale showed that the monthly average of climatic data explained 30% of the variance in wheat yield and the rest was explained by other environmental and management factors that varied in space and time (Lobell and Field, 2007). Iizumi and Ramankutty (2010) reported that more than 21% of the changes in the yield of the world's four main crops (wheat, corn, rice, and soybeans), which produce 60% of the total consumed calories, between 1981 and 2010 can be explained by changes in agroclimatic indicators.

3.2. Trend of of maximum temperature

Maximum temperature has had increasing trend (0.04 °C, 0.03 °C, and 0.01 °C per year) in four regions (Bojnord, Esfarayen and Shirvan, respectively) (Fig. 3).

Since wheat is not very compatible with humidity and high temperature, it is cultivated in tropical and semi-tropical regions at high altitudes and in cold times of the year (Flohr et al., 2018). The most suitable conditions for the satisfactory growth of wheat are wet and cold winter weather followed by warm, dry and clear weather for 6-8 weeks during the ripening period with an average temperature of 18-19 °C (Ali et al., 2019). It was reported that cold, drought, and extreme heat also decrease grain protein in wheat (Flohr et al., 2018). For wheat, the number of days when the air temperature was higher than 30 °C was calculated as an indicator of the aging speed throughout the growing season (Asseng et al., 2011; Lobell et al., 2012). In South Asia, for every one degree Celsius increase in temperature, 3-17% decrease in wheat yield has been observed (Ray et al., 2015).

3.3. Trend of of minimum temperature

Minimun temperature decreased throughout the region during all studied years (data not shown). The study of the sensitive stages of wheat growth during good years (with high grain) and poor years (with low grain yield) indicates that in poor years, the minimum temperatures were below the critical limit (-11 °C) (Fig. 6 and Fig. 7). The occurrence of very low temperatures in the initial stages of growth and production of primary leaves, which is the establishment stage of the plant, causes a decrease in the level of photosynthesis and as a result, a significant decrease in yield. The occurrence frequency of this variable is 92.1% of the studied years, thus, it is considered a limiting factor for the growth and development of wheat across the study area. Therefore, if the planting date is not properly chosen and the establishment and rooting of the plant is delayed, cold damage will reduce the yield. Phenological stages of plants occur late in cold regions and under low temperatures (Yalcin, 2017).

3.4. Trend of precipitation changes

Investigation of climatic variables during the growing season showed that precipitation during the last 38 years has had a decreasing trend (1.8 mm, 1.6 mm, and 0.41 mm per year) in three regions (Bojnord, Esfarayen and Farooj, respectively) (Fig. 4).

In each region, a period of time is considered for the planting of each plant, which is called the planting window (Row et al., 2000). This time depends on the time of the beginning of the rainfall rather than the amount of rainfall, which has high fluctuations among other aspects of wheat cultivation. In such a way that the delay in the beginning of autumn rains, at the same time as the decrease in temperature and lack of appropriates growth degree-day, affects the germination stage. The loss of seeds or the decline in seeds vigor, the increase in the production of infertile tillers, the sterility of flowers, the risk of the plant contracting diseases and pests should be considered as the consequences of early planting (Tahir and Nadeem, 2009). In the study that was carried out in Northeastern Iran in the conditions of climate change with two climate models HadCM3 and CGCM2 with two scenarios A2 and B2, the results showed that there is a positive and significant relationship between rainfed wheat grain yield and rainfall, as with increasing rainfall, wheat grain yield also increases (Bannayan and Eyshi Rezaei, 2012). In another study on South Australian wheat production, the possible effect of climate change on wheat yield was investigated using the DSSAT 3.5 model. The results showed that dry areas are more sensitive to climate change, especially changes in rainfall and temperature increase, also the average decrease in the probability of grain yield in all investigated areas was reported between 13.5 and 32% (Luo et al., 2003).

3.5. The changes of the length of wheat growing season

The decrease in precipitation and the simultaneous increase in temperature has caused the length of wheat growing season to be slightly reduced (regression coefficients in Fig. 5) to escape from adverse environmental conditions (Fig. 5). The highest amount of decrease during the growing season as a result of the increase in temperature (regression coefficient in Fig. 5) was related to Bojnord region (-0.9031 day per year) and the lowest was related to Esfarayen region (-0.2497 day per year). The other five regions had almost the same situation.

The appropriateness of wheat growth and phenology stages with the environmental conditions is one of the important factors for acclimatation, acclimatization and increase of wheat yield. In addition, so far, many researchers have reported the relationship between the duration of growth stages and the survival of yield components including the number of tillers, the number of spikes, the number of spikelets, the number of flowers and the number of seeds per square meter (Chavez-Herrera et al., 2018). Although wheat yield components are formed during different stages of plant growth, one month before flowering is a very important period in determining wheat grain yield. During this period, the stem and spike have their maximum growth rate and compete with each other to receive assimilates, which determines the rate of death of fertile florets in the flowering stage (Wang et al., 2017). The number of seeds in wheat is directly determined based on the number of fertile florets in the flowering stage (Steinfort et al., 2017). Due to the severe and negative impact of late season heat stress on yield, adaptive solutions and measures such as agronomical and breeding methods that allow wheat to escape from the interference of high temperatures with the stages of pollination and seed formation, including early planting (Krupnik et al., 2015), the use of special cultivation machines (zero tillage or minimum tillage), which reduces repetitive operations and saves time for land preparation, has been suggested (Amjath-Babu et al., 2016; Krupnik et al., 2013).

3.6. Panel Data Analysis (PDA)

The spatial and temporal effects of climatic variables on wheat grain yield in in seven regions from 1980 to 2009 years were identified using PDA. Given that the probability of *F* statistic ($p \leq 0.05$) , so the null hypothesis is rejected and we can say that the independent variables (number of occurrences and amount of precipitation during the growing season, the number and amount of precipitation in booting to the end of the soft paste stage, minimum, maximum and mean temperatures during the growing season, temperature and precipitation in the flowering phase and the length of the growing season) affect yield (Table 2).

The value of Durbin-Watson statistic is in the range of 1.5 to 2.5, so there is no correlation between the errors and the regression model is confirmed.

PDA identified the positive cross section effect for Bojnord (Table 2), so 2002 and 2007 were evaluated as good year and weak year with regard to wheat grain yield during the period 1980 to 2017, respectively (Table 3). Longer growing season (295 days vs. 269 days), amount and frequency of precipitation during the growing season (359.4 mm in 59 times, vs. 242.4 mm in 49 times), amount and frequency of precipitation in the booting to the end of grain milk stages (36.1 mm in 5 times vs. 13 mm in 3 times), increase in minimum temperatures during the period of primary leaf production and plant establishment (-15.1 °C vs. -21.2 °C), cool air in the flowering period, which is a sensitive stage to high temperatures (11.8 °C vs. 22.1 °C), respectively, increases the average yield in 2002 compared to 2007. Although the number of temperatures above 30 °C was higher in 2002 than in 2007 (11 vs. 3), it did not reduce yield in 2002 due to the late occurrence of the hard dough stage (Fig. 6).

The negative cross section effect for Farooj was identified by PDA, so 2009 and 2007 were evaluated as good year and weak year with regard to wheat grain yield during the period 1980 to 2009, respectively (data not shown). In 2007, the temperatures at the beginning of the growing season were so low that it faced negative temperatures during the early leaf production stage, and at the early stage of tillering and plant establishment, the air temperature reached to -20.9 ° C (Fig. 7). In 2007, at the flowering stage, the maximum temperature (198th days after planting) was 19.6 ° C and in 2009, the air temperature (15.1 °C) was cooler (Fig. 7). In 2007, the temperature reached to 30.7 ° C at grain filling stage (soft dough) and the increased temperature in this stage has caused grain shrinkage and reduced yield (Fig. 7). The length of the growing season in 2007 was five days shorter than in 2009, which by comparing the times of temperatures above 30 ° C, the amount and times of precipitation (Table 3 and Fig. 7) It can be attributed to the warm and dry growing season in 2007 compared with 2009.

The frequency of temperatures above 30 ^{o}C in all regions in the grain dough stage was higher than grain milk stage (Fig. 8).

The results showed that 63% of the changes in wheat yield in the regions are explained by the studied climatic variables (R^2= 0.63). Comparison of climatic variables showed that the number of temperatures above 30 degrees (N30TMAX), mean temperature (GSTMEAN), interaction of amount and frequency of precipitation (TPRAT×NPRAT) have a significant effect on yield ($p \leq 0.05$). The length of growing season was significant ($p \leq 0.05$) in all regions and had an additive effect. The p_{value} of *F-Limer* test was obtained less than 0.05 (Table. 3), so the data are not pooled (not cumulative) and the existence of cross-sectional effects between different regions for wheat is evident. In other words, three regions (Bojnourd, Shirvan and Esfarayen) have significant and positive cross-sectional constants effect in regard to the climatic variables (mean temperature, number of temperatures above 30 °C, amount and number of precipitation during the growing season) interval 1980-2009 and four regions (Farooj, Raz-Jargalan, Mane- Semelghan and Jajarm) had negative cross-sectional effects (Table. 4).

The results of PDA showed that wheat crop in all regions and in total of the studied years, the grain filling stage (grain milk and grain dough stages) was exposed to temperatures above 30 ° C and caused negative cross-sectional effects in four regions (Farooj, Raz-Jargalan, Mane-Semelghan and Jajarm). Temperatures above 30 ^{o} C can damage of leaf photosynthetic system and reduced grain filling period (Asseng et al., 2011). Critical limit of environmental variables for wheat in Northeastern Iran is 22.1 ^{o}C maximum temperature during anthesis phase, 33.9 ^{o}C maximum temperature, 7.8 ^{o}C mean temperature and 189.1 mm precipitation during growing season approximately (Table. 5).

Critical high and optimum temperature at grain filling stage were reported as 34.3 ^{o}C ± 2.66 and 21.3 ^{o}C ± 1.27, respectively (Farooq et al., 2011). At critically high temperatures higher than 32 ^{o} C prior to and during the anthesis stage, photosynthetic decline is more pronounced. This can cause pollen sterility, stigma desiccation, early embryo abortion, reduced seed set, shriveled seed, reduced seed size and setting. Optimum temperature in this stage is 23 ^{o}C ± 1.15 (Farooq et al., 2011; Lobell & Field, 2007; Reynolds et al., 2016). It seems that the shorter durability and continuity of high temperatures and its interaction with precipitation and mean temperatures has been the reason for the positive cross-sectional effects in areas (Table. 4). There is high probability of very low temperatures in the early leaves production and plant establishment stage. Therefore, the delay in planting date later than early October (common planting date across the study region), cause that the grain milk stage, which is more sensitive, will encounter high temperatures and will lead to a severe reduction in yield.

4. Conclusion

The average yield of irrigated wheat over 38 years, with a very gentle upward slope, has had an almost constant trend due to managerial factors including improved cultivars and mechanization level. Studying stress degree days and wheat phenology using AgMERRA data set as input for DSSAT crop model generated robust results which in turn can greatly enhance our understanding of somehow wheat growth responds to climate variability and could help farmers to adaptation and reasonably confront its influence. In general, the results showed that employing of the effective management methods, in particular selecting the appropriate planting date that could be resulted in better adaptation of the phenological stages of wheat to environmental conditions, can improve wheat yield.

Declarations

Supplemental Material

There are no supplemental materials included to the manuscript.

Ethics approval and consent to participate

This research meets all the ethical guidelines, including adherence to the legal requirements of our country.

Consent for publication

The authors confirm no conflict of interest and agree with the submission of the manuscript to the journal.

Data Availability

The software (DSSAT Ver. 4.7) was used in this study is available on the DSSAT.net - Official Home of the DSSAT Cropping Systems Model website (http://dssat.net) and after the fourth author's registration; the latest version (4.7) of the model was downloaded and employed. The authors had no special access or privileges that others would not have. All used and created data are available on demand.

Competing interests

The authors declare that they have no competing interests.

Funding Statement

The authors received no specific funding for this work.

Authors' Contributions

The authors of this research paper have directly participated in the planning, execution, or analysis of this study. The authors read and approved the final edition of the manuscript. CRediT author statement: Masoumeh Farhadi: data curation, software, formal analysis, writing-original draft preparation. Mohsen Jahan: project administration, investigation, writing-reviewing and editing. Mohammad Bannayan: conceptualization, methodology, validation.

Acknowledgement

Partially financial support of Vice President for Research and Technology, and Center of Excellence for Special Crops (CESC) of Ferdowsi University of Mashhad (FUM) is acknowledged. Authors would like to thank anonymous reviewers whose comments and suggestions were extremely valuable and helped improve this study.

References

1. Alexandrov, V., & Hogenboom, G. (2000). The impact of climate variability and change on crop yield in Bulgaria. Agricultural and Forest Meteorology, *104*(4), 315–327.
2. Ali, A., Haq, T. U., & Mahmood, R. (2019). Stimulating the Anti-Oxidative Role and Wheat Growth Improvement Through Silicon Under Salt Stress. Silicon, *11*, 2403–2406.
3. Amjath-Babu, T. S., Krupnik, T. J., Aravindakshan, S., Arshad, M., and Kaechele, H. (2016). Climate change and indicators of probable shifts in the consumption portfolios of dryland farmers in Sub-Saharan Africa: Implications for policy. *Ecological Indicators*, *67*(May 2020), 830–838. available from https://doi.org/10.1016/j.ecolind.2016.03.030
4. Angstrom, A. (1924). Solar and terrestrial radiation. Report to the international commission for solar research on actinometric investigations of solar and atmospheric radiation. Quarterly Journal of the Royal Meteorological Society, *50*(210), 121–126. https://doi.org/10.1002/qj.49705021008
5. Arshad, M., & Krupnik, T. S. A. T. J. (2016). Climate variability and yield risk in South Asia ' s rice – wheat systems: emerging evidence from Pakistan. https://doi.org/10.1007/s10333-016-0544-0
6. Arun, G., & Ghimire, K. (2019). Estimating post-harvest loss at the farm level to enhance Food Security: A Case of Nepal. International Journal of Agriculture, Environment and Food Sciences, *3*(September), 127–136. https://doi.org/10.31015/jaefs.2019.3.3
7. Asseng, S., Foster, I., & Turner, N.. (2011). The impact of temperature variability on wheat yields. Global Change Biology, *17*(2), 997–1012. https://doi.org/10.1111/j.1365-2486.2010.02262.x
8. Bannayan, M., Pooya Nasab, K., Ghorbani, R., & Yaghoobi, F. (2018). Temporal and Spatial Variation of Wheat and Beans Yield, Case Study: Khorasan Razavi. Iranian Journal of Field Crops Research, *16*(2), 263–282. https://doi.org/10.22067/gsc.v16i2.44536
9. Bannayan, M., Sanjani, S., Alizadeh, A. et al., (2010). Association between climate indices, aridity index, and rainfed crop yield in northeast of Iran. Field Crops Research, *118*(*2*), 105–114. https://doi.org/10.1016/j.fcr.2010.04.011
10. Batjes Niels H. (2012). ISRIC-WISE derived soil properties on a 5 by 5 arc-minutes global grid. *January 2012*. http://www.isric.org/sites/default/files/isric_report_2012_01.pdf

11. Bender, F. D., & Sentelhas, P. C. (2018). Solar Radiation Models and Gridded Databases to Fill Gaps in Weather Series and to Project Climate Change in Brazil Solar Radiation Models and Gridded Databases to Fill Gaps in Weather Series and to Project Climate Change in Brazil. Advances in Meteorology, *July*, 15. https://doi.org/10.1155/2018/6204382
12. Bosilovich, M. G., Akella, S., Coy, L., Cullather, R., Draper, C., Gelaro, R., Kovach, R., Liu, Q., Molod, A., Norris, P., Wargan, K., Chao, W., Reichle, R., Takacs, L., Vikhliaev, Y., Bloom, S., Collow, A., Firth, S., Labow, G., … Koster, R. D. (2015). Technical Report Series on Global Modeling and Data Assimilation, Volume 43 MERRA-2: Initial Evaluation of the Climate. *Technical Report Series on Global Modeling and Data Assimilation*, *43*(November).
13. Burroughs, W. (2003). Climate into the 21st Century. Cambridge University Press.
14. Chavez-Herrera, E., Hernández-Esquivel, A. A., Castro-Mercado, E., and García-Pineda, E. (2018). Effect of Azospirillum brasilense Sp245 Lipopolysaccharides on wheat plant development. Journal of Plant Growth Regulation, *37*(3), 859–866.
15. Curtis, T., & Halford, N. G. (2014). Food security: The challenge of increasing wheat yield and the importance of not compromising food safety. Annals of Applied Biology, *164*(3), 354–372. https://doi.org/10.1111/aab.12108
16. Fallah, mohammad hassan, nezami, ahmad, Khazaie, hamidreza, & nassiri mahallati, mehdi. (2021). Evaluation of DSSAT-Nwheat Model across a Wide Range of Climate Conditions in Iran. *Journal of Agroecology*, *12(4), 561–580*. https://doi.org/10.22067/jag
17. Farhadi, M., Jahan, M., & Bannayan, M. 2021. Investigation of Validity and Possibility of using AgMERRA Networked Dataset in North Khorasan Province. *Iranian Journal of Field Crops Research, 19(2), 201–217.* https://doi.org/10.22067/jcesc.2021.69532.1044
18. Farooq, M., Bramley, H., Palta, J. A., & Siddique, K. H. M. (2011). Heat stress in wheat during reproductive and grain-filling phases. Critical Reviews in Plant Sciences, *30*(6), 491–507. https://doi.org/10.1080/07352689.2011.615687
19. Flohr, B. M., Hunt, J. R., Kirkegaard, J. A., Evans, J. R., Trevaskis, B., Zwart, A., and Rheinheimer, B. (2018). Fast winter wheat phenology can stabilise flowering date and maximise grain yield in semi-arid Mediterranean and temperate environments. Field Crops Research, *223*, 12–25.
20. Gohari, A., Eslamian, S., Abedi-Koupaei, J., Massah Bavani, A., Wang, D., & Madani, K. (2013). Climate change impacts on crop production in Iran's Zayandeh-Rud River Basin. Science of the Total Environment, *442*(November), 405–419. https://doi.org/10.1016/j.scitotenv.2012.10.029
21. Iizumi, T., & Ramankutty, N. (2010). Changes in yield variability of major crops for 1981–2010 explained by climate change. Environmental Research Letters, *11*(3), 0. https://doi.org/10.1088/1748-9326/11/3/034003
22. Jahan, M., & Nassiri-Mahallati, M. (2022). Modeling the response of sesame (*Sesamum indicum* L.) growth and development to climate change under deficit irrigation in a semi-arid region. *PLOS Climate, 1(6): e0000003*. https://doi.org/10.1371/journal.pclm.0000003
23. Jain, M., Naeem, S., Orlove, B., Modi, V., & DeFries, R. S. (2015). Understanding the causes and consequences of differential decision-making in adaptation research: Adapting to a delayed monsoon onset in Gujarat, India. Global Environmental Change, *31*, 98–109. https://doi.org/10.1016/j.gloenvcha.2014.12.008
24. Joyce, R. J., Janowiak, J. E., Arkin, P. A., & Xie, P. (2004). CMORPH: A method that produces global precipitation estimates from passive microwave and infrared data at high spatial and temporal resolution. Journal of Hydrometeorology, 5(3), 487–503. https://doi.org/10.1175/1525-7541(2004)005<0487:CAMTPG>2.0.CO;2
25. Koocheki, A., Nassiri-mahallati, M., & Jafari, L. (2016). Evaluation of Climate Change Effect on Agricultural Production of Iran I. Predicting the Future Agroclimatic Conditions. *Iranian Journal of Field Crops Researc, 13(4), 651–664*. https://doi.org/10.22067/gsc.v13i4.51156
26. Krupnik, T. J., Uddin, Z., Timsina, J., Yasmin, S., Hossain, F., Al, A., Islam, A., and Mcdonald, A. J. (2015). Untangling crop management and environmental in fl uences on wheat yield variability in Bangladesh: An application of non-parametric approaches. *AGSY*, *139*, 166–179. available from https://doi.org/10.1016/j.agsy.2015.05.007
27. Krupnik, T. J., Santos Valle, S., Hossain, I., Gathala, M. K., Justice, S., Gathala, M. K., and McDonald, A. (2013). Made in Bangladesh: scale appropriate machinery for agricultural resource conservation in the context of smallholder farming. *International Maize and Wheat Improvement Center, Mexico City*.
28. Lewis, E., Chamel, O., Mohsenin, M., Ots, E., & White, E. T. (2018). Intergovernmental Panel on Climate Change. *Sustainaspeak*, 153–154. https://doi.org/10.4324/9781315270326-109
29. Lobell, D. B., & Burke, M. B. (2010). Agricultural and Forest Meteorology On the use of statistical models to predict crop yield responses to climate change. Agricultural and Forest Meteorology, *150*(11), 1443–1452. https://doi.org/10.1016/j.agrformet.2010.07.008
30. Lobell, D. B., & Field, C. B. (2007). Global scale climate-crop yield relationships and the impacts of recent warming. Environmental Research Letters, *2*(1), 7. https://doi.org/10.1088/1748-9326/2/1/014002
31. Luo, Q., Williams, M., Bellotti, W., & Bryan, B.A. (2003). Quantitative and visual assessments of climate change impacts on South Australian wheat production. Agricultural Systems, 77(3):173–186. https://doi.org/10.1016/S0308-521X(02)00109-9
32. Mourtzinis, S., Edreira, J. I. R., Conley, S. P., & Grassini, P. (2016). From grid to field: Assessing quality of gridded weather data for agricultural applications. European Journal of Agronomy. https://doi.org/10.1016/j.eja.2016.10.013
33. Nassiri-Mahallati, M., & Jahan, M. (2020). Using the AquaCrop model to simulate sesame performance in response to superabsorbent polymer and humic acid application under limited irrigation conditions. International Journal of Biometeorology, *64*(12), 2105–2117. https://doi.org/10.1007/s00484-020-02001-z
34. Nelson, G., MW, R., Koo J, R. R., T, S., & Al., E. (2009). Climate Change Impact on Agriculture and Costs of Adaptation. Title. *Washington, DC*: *Int. Food Policy Res. Inst*.
35. Poole, N. (2005). Cereal Growth Stages Guide (Issue 2). https://grdc.com.au/__data/assets/pdf_file/0031/364594/Cereal-growth-stages.pdf%0Ahttps://grdc.com.au/uploads/documents/GRDC Cereal Growth Stages Guide1.pdf VN - readcube.com
36. Prescott, J. (1940). Evaporation from a water surface in relation to solar radiation. Trans & Proc Roy Soc South Australia, *64*(1), 114–118.

37. Ray, D. K., Gerber, J. S., Macdonald, G. K., & West, P. C. (2015). Climate variation explains a third of global crop yield variability. Nature Communications, *6*, 1–9. https://doi.org/10.1038/ncomms6989
38. Raymundo, R., Asseng, S., Robertson, R., Petsakos, A., Hoogenboom, G., Quiroz, R., Hareau, G., & Wolf, J. (2018). Climate change impact on global potato production. *European Journal of Agronomy*, *100*(November 2016), 87–98. https://doi.org/10.1016/j.eja.2017.11.008
39. Ren, S., Qin, Q., Ren, H., Sui, J., & Zhang, Y. (2019). Heat and drought stress advanced global wheat harvest timing from 1981–2014. Remote Sensing, *11*(8). https://doi.org/10.3390/rs11080912
40. Reynolds, M. P., Quilligan, E., Aggarwal, P. K., Bansal, K. C., Cavalieri, A. J., Chapman, S. C., Chapotin, S. M., Datta, S. K., Duveiller, E., Gill, K. S., Jagadish, K. S. V., Joshi, A. K., Koehler, A. K., Kosina, P., Krishnan, S., Lafitte, R., Mahala, R. S., Raveendran, M., Paterson, A. H., … Yadav, O. P. (2016). An integrated approach to maintaining cereal productivity under climate change. Global Food Security, *8*, 9–18. https://doi.org/10.1016/j.gfs.2016.02.002
41. Rienecker, M. M., Suarez, M. J., & Gelaro, R. (2011). MERRA: NASA's Modern-Era Retrospective Analysis for Research and Applications. Journal of Climate, *24*(14), 3624–3648.
42. Ruane, A. C., Goldberg, R., & Chryssanthacopoulos, J. (2015). Climate forcing datasets for agricultural modeling: merged products for gap-filling and historical climate series estimation. Agricultural and Forest Meteorology, *200*, 233–248.
43. Sanjani, S., Bannayan, M., & Kamyabnejad, M. (2011). Detection of recent climate change using daily temperature extremes in Khorasan Province, Iran. Climate Research, *49*(3), 247–254. https://doi.org/10.3354/cr01031
44. Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., & Miller, H.. (2007). Climate Change 2007: governmental Panel on Climate Change The Physical Science Basis. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. https://doi.org/10.1256/wea.58.04
45. Sookhtanlo, M., & Sarani, V. (2019). Analysis of Factors Affecting on Risk Management of Wheat Production Agris on-line Papers in Economics and Informatics Analysis of Factors Affecting on Risk Management of Wheat Production Among Wheat Farmers (Razavieh Region, Khorasan-E-Razavi Province. February.
46. Steinfort, U., Trevaskis, B., Fukai, S., Bell, K. L., and Dreccer, M. F. (2017). Vernalisation and photoperiod sensitivity in wheat: Impact on canopy development and yield components. Field Crops Research, *201*, 108–121.
47. Tahir, M., & Nadeem, A. (2009). Effect of different sowing dates on growth and yield of wheat (*Triticum aestivum* L.) varieties in district Jhang, Pakistan. Pakistan Journal of Life and Social Sciences, *7*(1), 66–69.
48. Van Wart, J., Grassini, P., Yang, H., Claessens, L., Jarvis, A., & Cassman, K. G. (2015). Creating long-term weather data from thin air for crop simulation modeling. Agricultural and Forest Meteorology, *209–210*, 49–58. https://doi.org/10.1016/j.agrformet.2015.02.020
49. Van Wart J, Kersebaum KC, Peng S, Milner M, Cassman KG (2013) A protocol for estimating crop yield potential at regional to national scales. Field Crop Res., *143*:34–43. https://doi.org/10.1016/j.fcr.2012.11.018
50. Wallach D., Makowski D., and Jones J. W., Brun F. (2014). Working with dynamic crop models: Methods, Tools and Examples for Agriculture and Environment. Second Edidion. ISBN: 978-0-12-397008-4. https://doi.org/10.1016/C2011-0-06987-9
51. Wang, J.-Y., Xiong, Y.-C., Li, F.-M., Siddique, K. H. M., and Turner, N. C. (2017). Effects of Drought Stress on Morphophysiological Traits, Biochemical Characteristics, Yield, and Yield Components in Different Ploidy Wheat. *Advances in Agronomy;*, 139–173.
52. White, J. W., Hoogenboom, G., Stackhouse, P. W., & Hoell, J. M. (2008). Evaluation of NASA satellite- and assimilation model-derived long-term daily temperature data over the continental US. *Agricultural and Forest Meteorology, 148, 1574–1584.* https://doi.org/10.1016/j.agrformet.2008.05.017
53. Willmott, C. J., Ackleson, S. G., Davis, R. E., Feddema, J. J., Klink, K. M., Legates, D. R., O'Donnell, J., & Rowe, C. M. (1985). Statistics for the evaluation and comparison of models. Journal of Geophysical Research, *90*(C5), 8995. https://doi.org/10.1029/jc090ic05p08995
54. Yalcin, H. (2017). Plant phenology recognition using deep learning: Deep-Pheno. *Y 6th International Conference on Agro-Geoinformatics. 7–10 August, Fairfax, VA, USA. DOI: 10.1109/Agro*-Geoinformatics.2017.8046996.

Tables

Table 1. Geographical coordinates and properties of seven synoptic stations in Northeast, Iran

Longitude and latitude						**Elevation from the sea (m)**	**Established year**	**Synoptic Stations**
Northern Latitude			**Eastern longitude**					
Second	**Minute**	**Degree**	**Second**	**Minute**	**Degree**			
56	2	37	41	29	57	1203	2007	Esfarayen
55	33	37	43	56	56	762	2006	Mane-Semelghan
48	28	37	18	16	57	1100	1977	Bojnord
43	57	36	17	20	56	969	2007	Jajarm
23	56	37	5	6	57	1278	2006	Raz-Jargalan
4	26	37	15	50	57	1051	2005	Shirvan
15	13	37	36	13	58	1196	2008	Farooj

Table. 2 Panel data analysis to determine the effects of environmental variables on wheat grain yield in Northeast, Iran from 1980 to 2009 years

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	-13567.99	2236.367	-6.066978	0.0000
N30TMAX	20.51323	8.314688	2.467107	0.0144
GSTMIN	-17.88020	19.66559	-0.909212	0.3642
GSTMEAN	817.4941	82.91990	9.858841	0.0000
GSTMAX	10.20361	22.83074	0.446924	0.6554
ASTMAX	-6.044855	8.794025	-0.687382	0.4926
ASPRAT	-2.417837	8.944842	-0.270305	0.7872
GS	32.23145	5.897515	5.465260	0.0000
TPRAT40_80*NPRAT40_80	-0.136304	0.252038	-0.540808	0.5892
TPRAT*NPRAT	0.044283	0.008792	5.036719	0.0000
	Weighted Statistics			
R-squared	0.635942	Mean dependent var		3322.484
Adjusted R-squared	0.609585	S.D. dependent var		1275.487
S.E. of regression	567.7592	Sum squared residual		71239469
F-statistic	24.12789	Durbin-Watson stat		1.806150
Prob(F-statistic)	0.000000			
Effects Test (F-Limer)	Statistic	d.f.	Prob.	
Cross-section F	24.687395	(7,221)	0.0000	
Cross-section Chi-square	137.495062	7	0.0000	

N30TMAX (Number of 30< degree centigrade at growth season), GSTMIN (Minimum temperature at growth season), GSTMEAN (Mean temperature at growth season),GSTMAX (Maximum temperature at growth season), ASTMAX (Maximum temperature at anthesis stage), ASPRAT (Precipitation at anthesis stage), GS (Growth season)

Table. 3 Comparison of environmental variables affecting wheat yield in Northeast, Iran in good (2002) and weak (2007) years with regard to grain yield during 1980-2017

Amount of precipitation (mm) during booting to the end of grain milk stage	Number of precipitation during booting to the end of grain milk stage	amount of precipitation in the flowering phase (mm)	Number of precipitations during the growing season	amount of precipitation during the growing season (mm)	Maximum temperature in flowering phase (∘c)	Minimum temperature during the growing season (∘c)	Average temperature during the growing season (∘c)	The number of occurrences of temperatures above 30 degrees during the growing season	Maximum temperature during the growing season (∘c)
36.1	5	0	59	359.4	11.89	-15.1	5.84	11	33.9
13	3	0	49	242.4	22.1	-21.29	5.82	3	30.7

Table. 4 The Cross section fix effect for the studied regions in Northeast, Iran

Region	Effect
Bojnord	1247.209
Shirvan	936.0465
Esfarayen	733.8508
Farooj	-624.2577
Raz Jarglan	-847.541
Mane-Semelghan	-933.3697
Jajarm	-1722.815

Table. 5 Critical limits of environmental variables for wheat in Northeast, Iran

Region	Maximum temperature during growth season (ºC)	maximum temperature during anthesis phase (ºC)	mean temperature during growth season (ºC)	precipitation during growing season
Bojnord	30.7	22.1	5.82	242.4
Esfarayen	32.4	19.6	6.49	192.6
shirvan	31	23.6	6.25	184.5
Farooj	34.9	19.6	7.94	164.9
Mane-semelghan	36.4	25.5	9.1	182.2
Raz-Jargalan	35.6	23.2	8.24	190.4
Jajarm	36.3	22	10.69	167.1
Mean	33.9	22.2	7.8	189.1

Figures

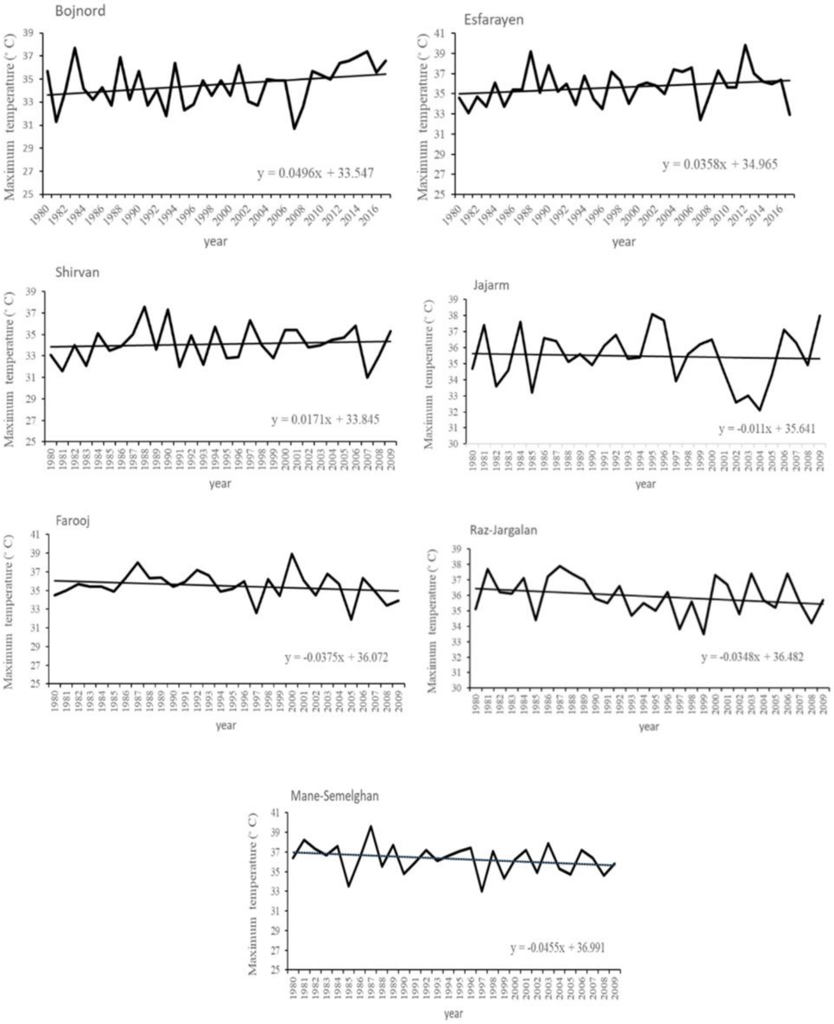

Figure 1

Trend of changes in the wheat average yield (kg ha^{-1}) resulted from management factors for seven studied regions in Northeastern Iran

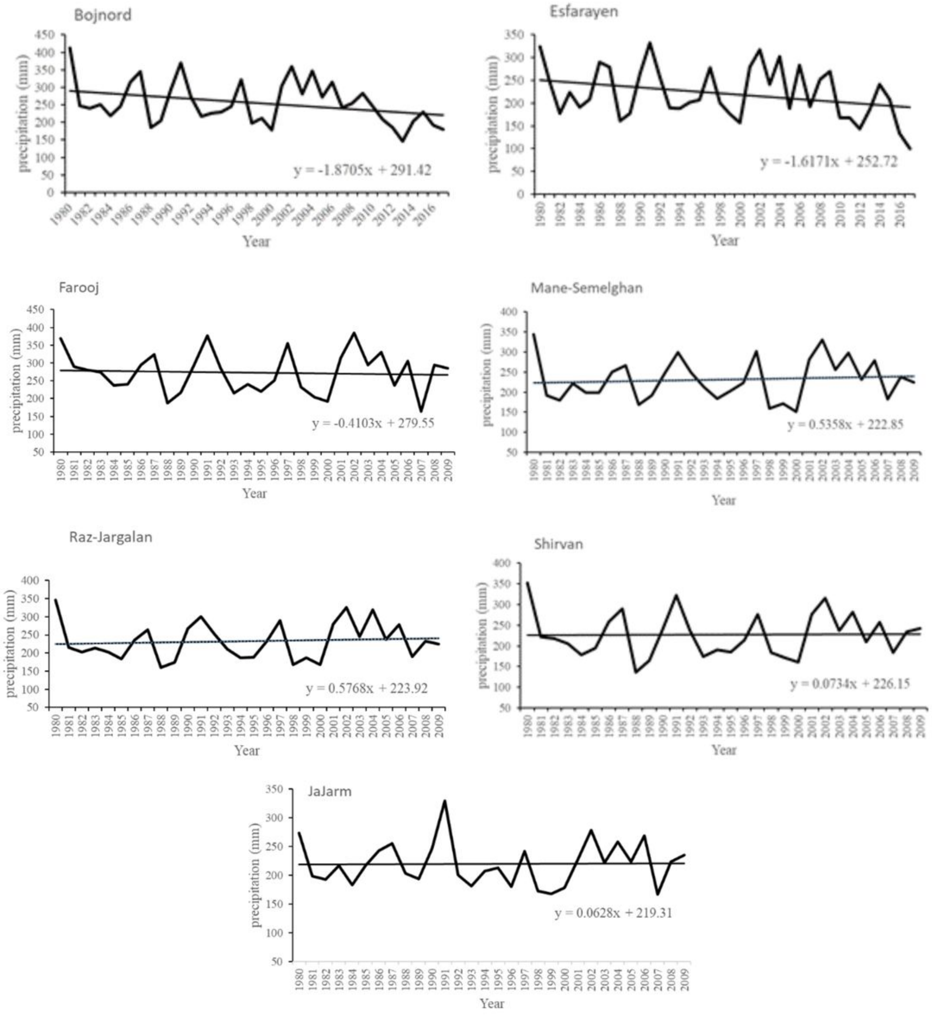

Figure 2

Comparison of observational and estimated yield (kg ha^{-1}) of wheat for seven studied regions in Northeastern Iran

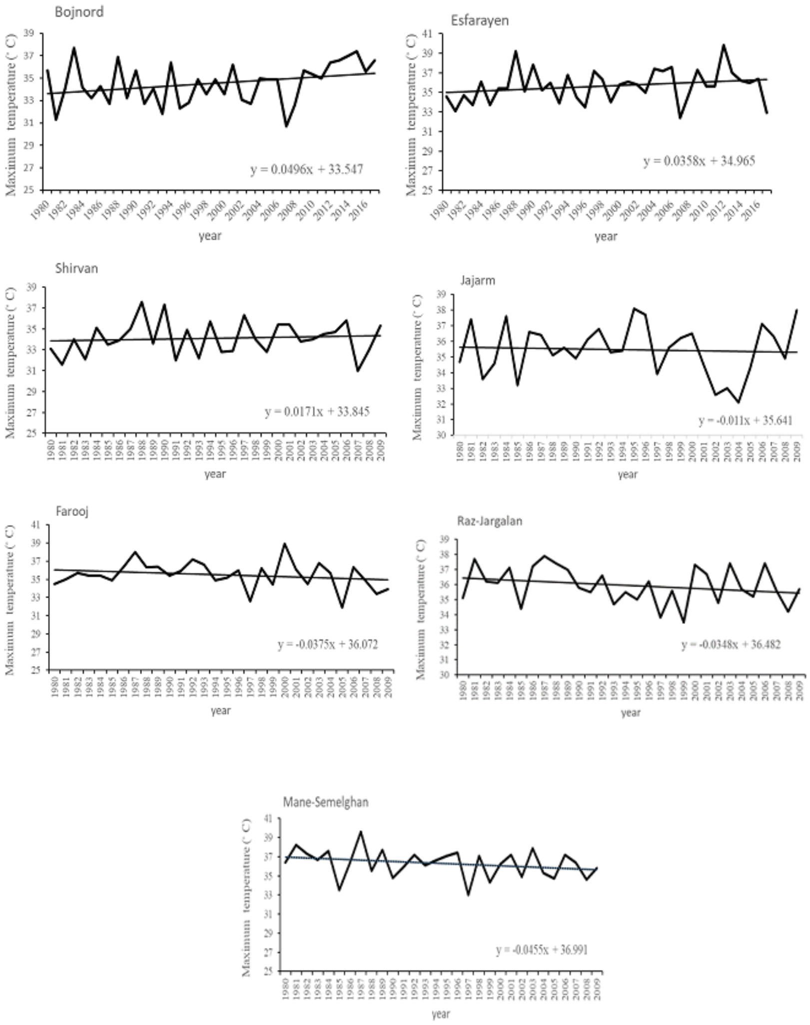

Figure 3

Trend of changes in maximum temperature during growing season of wheat for seven studied regions in Northeastern Iran

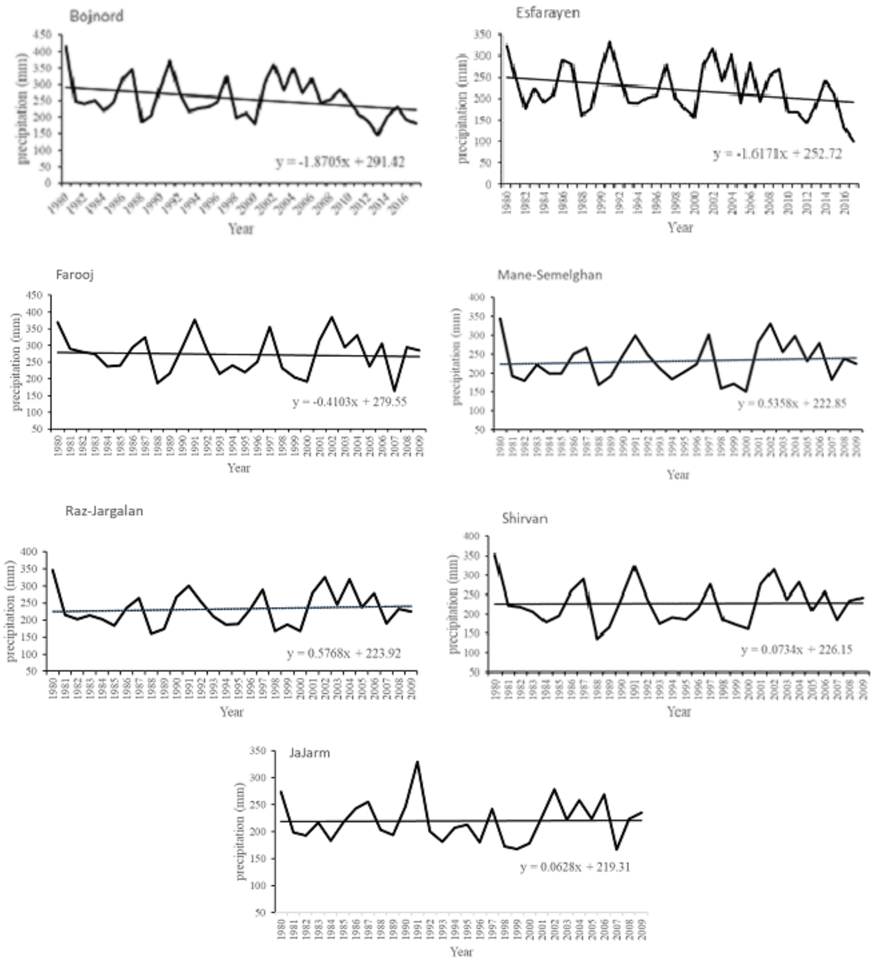

Figure 4

Trend of changes in precipitation variables during growing season of wheat for seven studied regions in Northeastern Iran

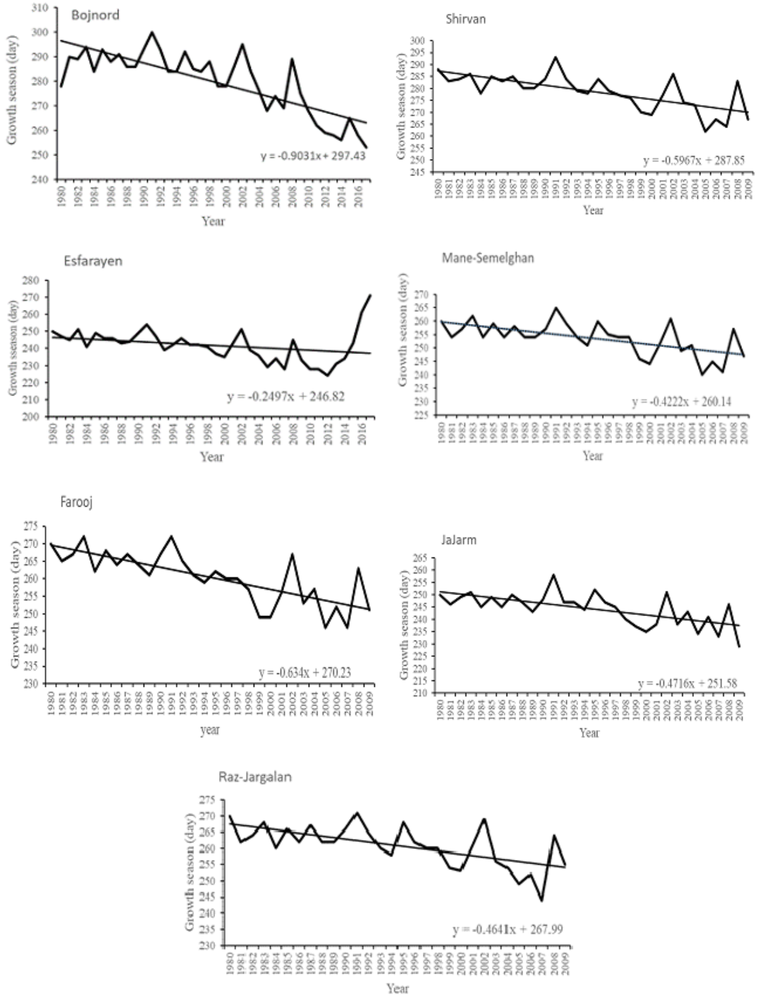

Figure 5

Trend of changes in growing season of wheat for seven studied regions in Northeastern Iran

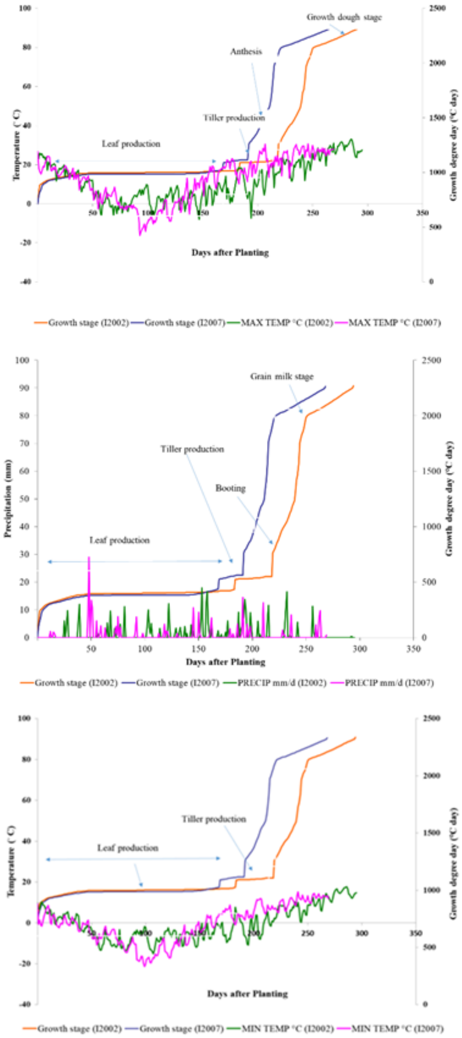

Figure 6

Maximum temperature (up), minimum temperature (middle) and precipitation (below) changes during the growth stages of wheat in good year (2002) and weak year (2007) with regard to grain yield in Bojnord at Northeastern Iran

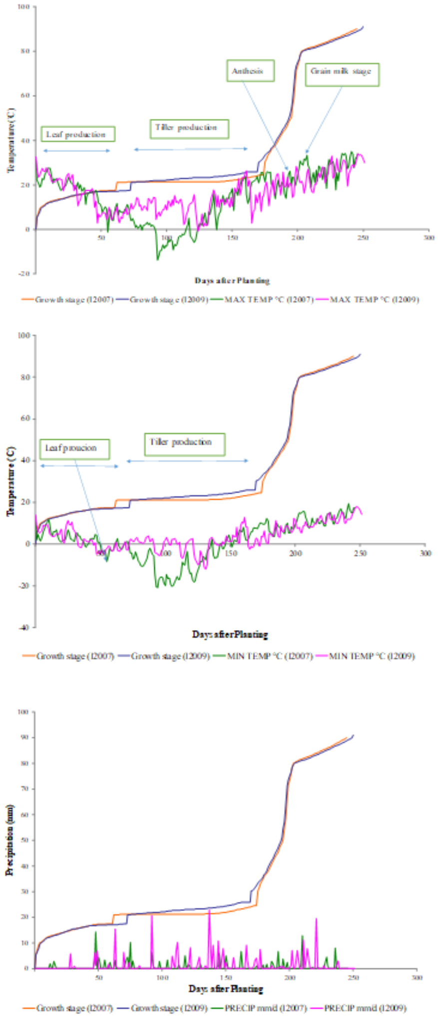

Figure 7

Maximum temperature (up), minimum temperature (middle) and precipitation (below) changes during the growth stages of wheat in good year (2009) and weak year (2007) with regard to grain yield in Farooj region at Northeastern Iran

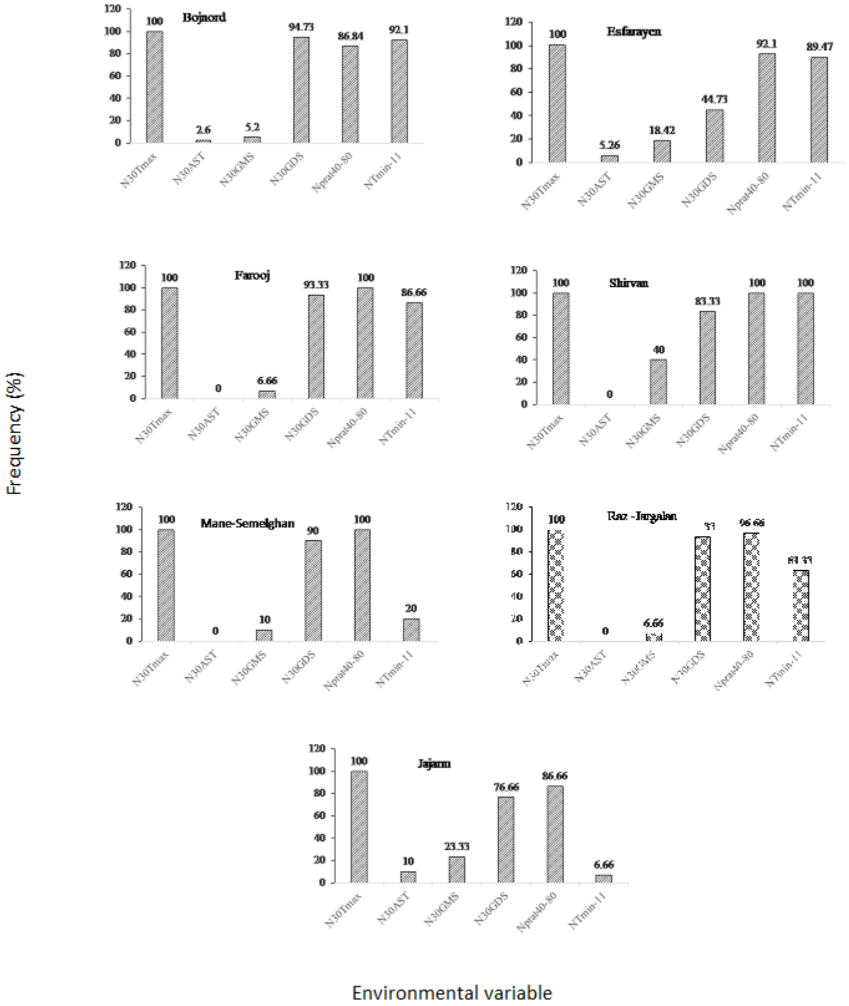

Figure 8

Frequency of occurrence of climatic variables for seven studied regions in Northeastern Iran

(Bojnord and Esfarayen, 1980-2017; Shirvan, Farooj, Mane-Semelghan, Raz-Jargalan and Jajarm, 1980-2009).

N30Tmax (number of 30< degree centigrade at growth season), N30AST (number of 30< degree centigrade at antheseis stage), N30GMS (number of 30< degree centigrade at grain milk stage), N30GDS (number of 30< degree centigrade at grain dough stage), Nprat40-80 (number of precipitation at growth season), NTmin-11 (number of -11> degree centigrade at growth season)